Research on the International Space Station – An Overview[1]

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The International Space Station (ISS) celebrates ten years of operations in 2008. While the station did not support permanent human crews during the first two years of operations—November 1998 to November 2000—it hosted a few early science experiments months before the first international crew took up residence. Since that time—and simultaneous with the complicated task of ISS construction and overcoming impacts from the tragic *Columbia* accident—science returns from the ISS have been growing at a steady pace. As of this writing, over 162 experiments have been operated on the ISS, supporting research for hundreds of ground-based investigators from the U.S. and international partners. This report summarizes the experimental results collected to date. Today, NASA's priorities for research aboard the ISS center on understanding human health during long-duration missions, researching effective countermeasures for long-duration crewmembers, and researching and testing new technologies that can be used for future exploration crews and spacecraft. Through the U.S. National Laboratory designation, the ISS is also a platform available to other government agencies. Research on ISS supports new understandings, methods or applications relevant to life on Earth, such as understanding effective protocols to protect against loss of bone density or better methods for producing stronger metal alloys. Experiment results have already been used in applications as diverse as the manufacture of solar cell and insulation materials for new spacecraft and the verification of complex numerical models for behavior of fluids in fuel tanks. A synoptic publication of these results will be forthcoming in 2009.

At the 10-year point, the scientific returns from ISS should increase at a rapid pace. During the 2008 calendar year, the laboratory space and research facilities were tripled with the addition of ESA's *Columbus* and JAXA's *Kibo* scientific modules joining NASA's *Destiny* Laboratory. All three laboratories, together with external payload accommodations, support a wide variety of research racks and science and technology experiments. In 2009, the number of crewmembers will increase from three to six, greatly increasing the time available for research. The realization of the international scientific partnership provides new opportunities for scientific collaboration and broadens the research potential on the ISS. Engineers and scientists from around the world are working together to refine their operational relationships and build from their experiences conducting early science to ensure maximum utilization of the expanded capabilities aboard ISS. This paper will summarize science results and accomplishments, and discuss how the early science utilization provides the foundation for continuing research campaigns aboard the ISS that will benefit future exploration programs.

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I. Introduction

THE first fifteen expeditions (2000-2007) aboard the International Space Station (ISS) have established the ISS as a laboratory providing a unique opportunity for research capabilities. This paper reviews the science accomplishments achieved by the collaborative efforts of researchers, crewmembers, and the ISS Program.

Early Space Station science utilization, while an important part of crew activities, competed with ISS assembly and maintenance, anomaly resolution, and the re-planning efforts required after the *Columbia* accident. Simply learning to live on and operate the ISS consumed a large percentage of the efforts onboard ISS. Despite the environment of construction and system shake-downs that dominated the early years, important science activities were conducted.

In 2005, the ISS Program Scientist's Office created an online experiment database, aimed at tracking and communicating ISS scientific research[1] and published a summary of all of the US experiments and their results through Expedition 10 (April 2005)[2]. Today, this database is continuously updated; it captures ISS experiment summaries and results, and functions as a reference used for planning ISS science operations. An important aspect of the database is the inclusion of scientific publications from all ISS experiments as they become available. To date, more than 200 results publications and research summaries have been included in the database; the number continues to grow at a steady pace[3]. Additional science data and results have been discussed in scientific symposia, with publications pending. The scientific findings support future research and guide upcoming exploration activities.

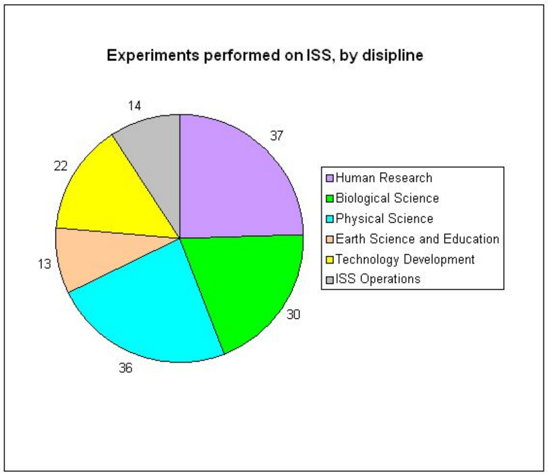

Figure 1. Distribution by discipline of NASA's ISS experiments for Expeditions 0 – 15 (On-orbit activities from 2000-2007).

NASA's research activities on the ISS span several scientific fields, including exploration technology development, microgravity research in the physical and biological sciences, human research for exploration, Earth science and education. Data from ISS operations have been used in additional research on crew health, the ISS structure, and the ISS environment. Figure 1 is a graphical representation of the distribution of ISS experiments by discipline, based on the number of experiments performed through the first fifteen expeditions (from 2000-2007). A synoptics publication including all the research and results completed on ISS is forthcoming in 2009[4].

II. ISS Research Results

A. Technology Development for Exploration

One of NASA's top priorities for research aboard the ISS is the development and testing of new technologies and materials considered for future exploration missions. To date, 22 different technology demonstrations have been performed. These experiments include research characterizing the microgravity environment, monitoring the ISS environment both inside and outside the spacecraft, testing spacecraft materials, developing new spacecraft systems, testing picosatellites and new satellite commanding and controls. We are tracking 34 scientific publications and recognize that classified and proprietary proceedings include a much greater number of results documenting technology developments. Recent experiments range from combustion physics and soot production (important data for redesign of spacecraft smoke detectors[5]) to the successful demonstration of microfluidic technologies for rapidly detecting different contaminants like bacteria and fungi. Other new technology experiments and stand-alone instrument packages monitor other air contaminants.

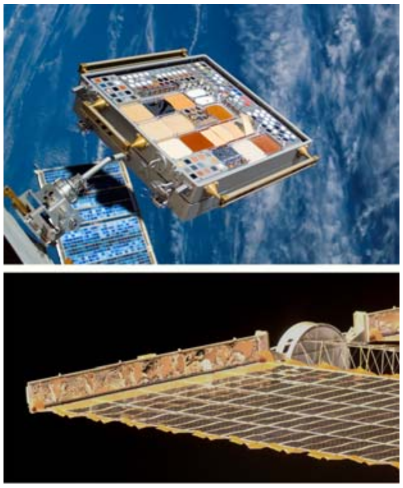

Figure 2. Top: MISSE-3 experiment on the ISS, Exposing samples to the space environment. Bottom: Atomic oxygen damage to materials on an ISS solar array blanket box.

One of the most prolific series of investigations on the ISS is the Materials International Space Station Experiment (MISSE). The MISSE series (Fig. 2) tests how spacecraft materials withstand the harsh space environment, including solar radiation, atomic oxygen erosion, thermal cycling, micrometeorite and orbital debris impacts, and contamination from spacecraft. Hundreds of materials have been tested to date. MISSE results have been used to understand and calibrate how materials already in use on spacecraft degrade in the space environment[6] (for example, polymers used for insulation, and solar array materials) and predict the durability of new materials (e.g. the solar cells planned for the Commercial Orbital Transportation System). Samples currently being tested on the ISS include materials that are part of the design of the new Orion vehicle. In addition to several recent and upcoming publications, MISSE investigators have devised methods for measuring atomic oxygen erosion yields, and assembled data that will provide important reference for designers, developers and builders of future spacecraft and instruments. The MISSE team has also spearheaded innovative collaborations between industry, academia, NASA and the Department of Defense, including hundreds of investigators.

B. Physical Sciences in Microgravity

The research themes of the microgravity program in the physical sciences have shifted since 2000. Over the first fifteen expeditions (through October 2007), 33 physical science experiments were performed, yielding more than 40 publications. Early physical science experiments emphasized growth of protein crystals in microgravity conditions, investigating fundamental properties in fluids, and early experiments investigating specific behaviors of colloids. Today, a major research thread sponsored by NASA on the ISS focuses on the fundamental properties of colloids and complex fluids, part of the relatively new field of the physics of soft matter[7]. The fundamental properties of these materials are determined by the behaviors and properties of the particles, and their tendency to assemble or cluster into particular structures, depending on conditions. Microgravity research enables the definition of phase boundaries, responses to directional forces other than gravity, and interactions without convection. Several experiments have examined basic phase transitions (solid-liquid-gas transitions) in the absence of gravitationally-induced complications like density stratification of materials.

While ISS research addresses questions framed by fundamental physics and chemistry, the results often have very practical applications for future exploration technologies and on Earth. For example, a demonstration of capillary flow of fluids in microgravity (Capillary Flow Experiment, CFE, designed to record the flow of fluid in containers with different geometries) produced the first-space-validated numerical models describing this fluid behavior[8]. The research to describe capillary flow in microgravity is important for management of large volumes of fluids in space; results will be benchmarked and applied to designs of fuel tanks, and other spacecraft fluid systems.

Another experiment, InSPACE (Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsion) provided new observations and unexplained structures and transitions of structures in magnetically-controlled fluids called magnetorheologic fluids (fluids with suspended iron particles that cluster and form structures when subjected to a magnetic field, causing rapid changes in viscosity of the fluid). Microgravity allows for longer observations of the formation of the magnetic particle aggregates, and their structures and kinetics[9]. For these experiments, the availability of a long-term laboratory environment on the ISS has facilitated the development and completion of additional experiments to explore unexpected structures observed during InSPACE sample runs. Magnetically-controlled materials have widespread applications in several industries including robotics, the automotive industry (e.g., suspension and damping systems) and civil engineering (e.g., bridges, earthquake-protection systems).

Microgravity physics experiments include other colloidal systems that examine the clustering properties of colloidal particles in microgravity. These experiments complement the fast growing field

Facility	Purpose
Cellular Biotechnology Operations Support System (CBOSS)	Cell incubator; supports multiple experiments
Commercial Generic Bioprocessing Unit (CGBA)	Bioprocessor for microorganisms; programmable, accurate temperature control
Advanced Astroculture™ (ADVASC)	Plant growth unit
Biomass Production System (BPS)	Microgravity plant growth environment with environmental control subsystems.
Microencapsulation electrostatic processing system (MEPS)	Automated system used to produce liquid-filled micro-balloons
Plant Generic Bioprocessing Appartus (PGBA)	Closed chamber plant growth facility with light, moisture, temperature, and gas control
Group Activation Pack-Fluid Processing Apparatus (GAP-FPA)	Test tube system for controlled, sequential mixing of 2 or 3 fluids in microgravity.

Table 1. Biotechnology support hardware tested as part of early ISS utilization.

of research in colloids and complex fluids, with many potential applications in both commercial and exploration sectors – from plastics to household cleaning and personal hygiene products to the manufacture of new high technology materials.

C. Biological Sciences in Microgravity

Through Expedition 15 (October 2007), twenty-seven different biological experiments were performed on the ISS. The early experiments were centered on testing new biotechnology tools (Table 1). Cellular biology and parameters of plant growth affected by microgravity also comprised a large percentage of the research. Experiments on animal biology and microbiology were also conducted. To date, we have collected 25 publications reporting results from biological research on the ISS.

One of the most exciting results reported from ISS research is the confirmation that common pathogens change and become more virulent during space flight[10]. The Microbe (Effect of Spaceflight on Microbial Gene Expression and Virulence) experiment was performed in September 2006; it examined changes in three microbial pathogens. Initial data from one of the microbes, *Salmonella typhimurium* (a leading cause of human gastroenteritis), showed that 167 genes were expressed differently in flight when compared with ground controls. The data indicated a response to the microgravity environment, including widespread alterations of gene expression that increased disease-causing potential. These results show great promise for both understanding mechanisms used by pathogens to spread disease and also designing ways to better protect humans in space[9]. With these new insights, similar experiments will continue on the ISS with related sets of pathogens. The original experiment was funded because of the human health risks for exploration missions, but because of the potential for applications to prevent disease on Earth, follow-on studies have been implemented as pathfinders for the use of the ISS as a National Laboratory.

D. Human Research Program

Research on the human body in space—how it reacts to microgravity and radiation—is a high priority for NASA's ISS science portfolio (Fig. 2). The Human Research Program (HRP) experiments aboard the ISS build from the large body of work collected since the early days of space program, including a robust set of experiments conducted on *Skylab*, *Mir* and shorter duration Shuttle flights. Clinical evidence demonstrated important physiological changes in astronauts during space flight. The HRP, together with ISS Medical Operations sponsored experiments that study different aspects of crew health, and efficacy of countermeasures for extended duration stays in microgravity. Up through the fifteenth ISS expedition (October 2007), 32 experiments focused on the human body, including research on bone and muscle loss, the vascular system, changes in immune response, radiation studies, and research on psycho-social aspects of living in the isolation of space. Several of the early experiments have led to new experiments, testing details of observations or pursuing new questions raised by early results. One or two new experiments are started nearly every expedition (Fig. 3).

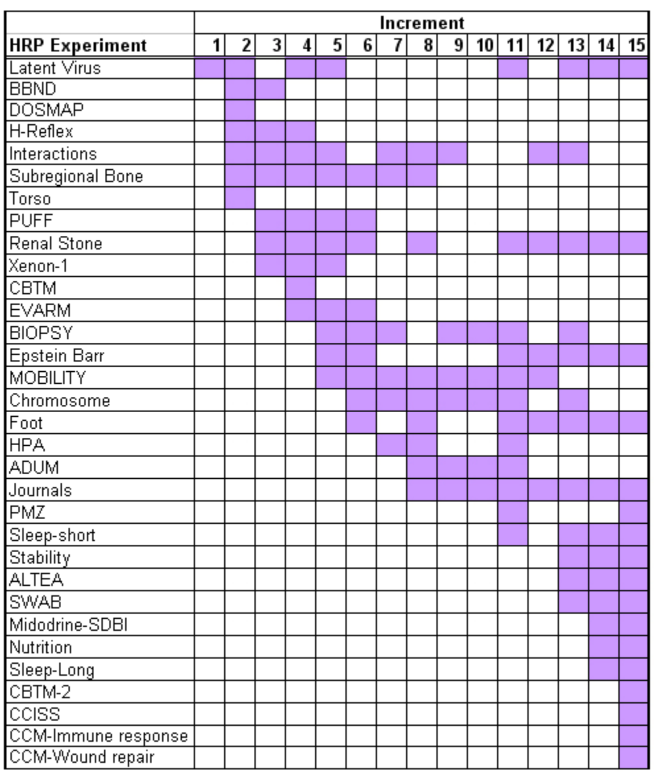

Figure 3. Experiments relevant to human physiology in space, listed by ISS expedition. The Human Research Program (sponsor of most of these experiments) has initiated new experiments nearly every expedition.

The HRP research now focuses on knowledge gaps in our understanding of the physiological changes observed during long-duration space flight and research aimed at ameliorating the greatest health risks[11]. Today, an integrated set of parameters are monitored on ISS crewmembers to provide the information needed to design and validate countermeasures for human exploration beyond Earth orbit. For example, Nutrition (Nutritional Status Assessment), a comprehensive in-flight study of human physiologic changes during long-duration space flight[12], and Integrated Immune (Validating Procedures for Monitoring Crew member Immune Function) sample and analyze participant's blood, urine, and saliva before, during and after flight. These samples are used to study changes related to functions like bone metabolism, oxidative damage and immune function. These studies are unique because of the information they collect on the timing of changes during the course of the space mission. Another collaborative set of experiments measure and monitor body fluid shifts; electrocardiograms are collected to monitor the heart function and vascular health of the crew. The crew periodically tests their pulmonary function, and keeps journals that are used to quantitatively analyze their response to isolation. Future research is also ensured. Extra biological samples are collected for the Repository investigation—a long-term archive of critical biological samples collected from ISS crewmembers—for future analysis when new tools and methods can be used and new questions are posed.

Results from the initial experiments on the ISS are just now being published; most studies require multiple subjects over several years in order to derive the necessary data. Nevertheless, we have already identified 43 scientific publications from research sponsored by the Human Research Program performed on ISS. These results document, in increasing detail, locations and parameters of bone loss, links between bone and muscle loss, renal stone development, rates of recovery and changes in recovered bone mass, changes related to the immune system, associated profiles of other physiological or biochemical parameters, and roles of diet, drug countermeasures, and exercise. Compilations that include the collective results and collaborations of ground and space-based human research experiments have also been published (e.g. [13]). Since many of the human research studies continue aboard the ISS, results will continue to flow in from the early experiments.

E. Observing the Earth and Educational Activities

The crew continues to perform the Crew Earth Observations (CEO) investigation that supports a variety of Earth Science initiatives. Crew observations document urban growth, monitor changes along coastlines and long-term ecological research sites, record major events like volcanic eruptions or hurricanes, and provide observations to support the International Polar Year. In a recent example, researchers working with the National Snow and Ice Data Center requested images of icebergs that broke from the Larsen ice shelf in Antarctica. The high resolution ISS images provided the first observations of ponded meltwater on the icebergs as they drifted into the South Atlantic Ocean (Fig. 4). These data allowed scientists to use the icebergs as analogs of ice sheets and model the accelerated breakup of an ice shelf[14]. While Earth observation activities have less formal experiment protocols, the data are fully accessible to scientists around the world. ISS Earth observations have supported more than 20 publications and 1 patent, several web-based articles and a robust database that serves more than 325,000 images of Earth taken by astronauts on the ISS (http:// eol.jsc.nasa.gov).

Figure 4. ISS astronauts working with scienists studying the breakup of Antarctic ice shelves, tracked Iceberg A39B near South Georgia Island, as it collected ponded meltwater on the surface and disintergratedin the South Atlantic Ocean. NASA image ISS008-E-12558.

The ISS education activities have touched millions of students around the world[15]. For example, tens of thousands of students have participated in the EarthKAM experiment; even more have participated in crew conferences with schools through HAM radio. In addition, crews continue to create short videos demonstrating elements of life in microgravity, profiling technologies involved in living off of the planet, and providing a behind-the-scenes look at some of the science experiments on the ISS. Recent examples include a feature called "Toys in Space"[16] and a demonstration of Newton's Laws.

F. Science from ISS operations

The formal experiments performed on the ISS, and their published results, represent part of the body of ISS research supported by NASA. For example, some ISS crewmembers initiate their own experiments and demonstrations of microgravity phenomena (e.g. Saturday Morning Science[17]). Ground studies in analog settings, experiments that refine techniques or instrumentation, and follow-on studies to the ISS experiments support almost all of the specific research projects performed on the ISS. Beyond the continued experimentation, analysis and reporting of peer-reviewed research, there is a large body of science (at least 30 publications) resulting from data collected from day-to-day operations of the ISS. These data and their analyses are critical for future exploration. They document daily parameters of the crew and the spacecraft, verify as-built configurations and responses of hardware, record changes over time in configurations, document the space environment (radiation, micrometeoroid orbital debris (MMOD) flux, local contamination from outgassing and venting, daily wear due to thermal flexing), and the efficacy of countermeasures like MMOD and radiation shielding.

III. ISS Research: Benefits to Life on Earth

A. Spinoffs and Patents

We continue to track innovations resulting from research in microgravity. Several recent patents and partnerships have demonstrated back-to-Earth benefits of the public investment in ISS research. A few examples are provided here.

- The air purifying technology (TiO2-based ethylene) employed in the plant growth chamber used in the ADVASC (Advanced Astroculture™) experiment was incorporated into an airborne pathogen scrubber that is effective against Anthrax spores[18].
- A researcher mining the public database of astronaut photographs of the Earth (http://eol.jsc.nasa.gov) for oblique views of large fans of sediments around river systems (fluvial fans) assembled and patented a compilation of the global distribution of these features. This work has implications for hydrocarbon exploration[19].
- An ISS investigator recently patented the Microparticle Analysis System and Method, an invention for a device that detects and analyzes microparticles[20]. This technology supports the chemical and pharmaceutical industries, and is one of a sequence of inventions related to technology development for experiments on the ISS and Shuttle, including the MEPS (Microencapsulation Electrostatic Processing System) experiment that demonstrated microencapsulation processing of drugs, a new and powerful method for delivering drugs to targeted locations. Also of note, the ISS demonstration of the microencapsulation of drugs has now been reproduced on the ground[21].
- The investigator for the BCAT-3-4-CP (Binary Colloidal Alloy Test -3 and 4: Critical Point) was facing a challenge using a microscope to observe the dynamic clustering behavior of his colloidal experiments: the moving clusters of colloidal beads would move out of the field of view. The investigator developed a target-locking technology for his microscope[22].
- The MISSE series have yielded dozens of important assessments directly applicable to current and future spacecraft materials. Additionally, spinoffs include the use of atomic oxygen to remove organic content from surfaces for diverse applications. Examples include use of atomic oxygen to restore valuable artwork, and to remove bacteria contaminants from surgical implants. A recent patent was awarded to etch the surface of optical fibers used for blood analyses to increase the surface area and enable rapid assessment of blood glucose levels[23,24].

B. Education: Benefits to the Next Generation of Space Explorers

Supporting Science, Technology, Engineering and Mathematics (STEM) education is an important component of all ISS research; the estimated educational impact of the collection of ISS research is broad. In 2006, Thomas et al[13] estimated that more than 30 million students and nearly 15,000 teachers had participated in ISS scientific activities or demonstrations. Specific educational activities are part of every ISS research complement, and include student-developed experiments, students performing classroom versions of ISS experiments and demonstrations, and stand-alone educational demonstrations that can be used as teaching aids or resource materials. In one large coordinated effort, the first educator astronaut flew to the ISS in December 2006 and conducted classroom sessions throughout her mission.

In addition to these education activities, many research experiments are tied to a US academic institute and involve student research from high school through advanced graduate degrees. Students may be listed as co-investigators, involved in hardware development or testing, or participate in critical parts of operations and data reduction. For example, two investigators for the MISSE-2 (Materials International Space Station Experiment-2) enlisted high school students for sample preparation, and subsequent data analysis of their polymer samples that were mounted on the MISSE-2 container for exposure to the space environment. These samples, called the PEACE (Polymer Erosion and Contamination Experiment) polymers, are now being examined to determine the effects of atomic oxygen erosion[25,26]. Students involved in the MISSE PEACE polymer experiments have successfully competed in science fairs and demonstrations, and have gone on to pursue degrees in science from top universities. A team of three young women that participated in the PEACE polymer studies placed sixth in the prestigious National Siemen's Competition in Math, Science and Technology. For their work, the team received medals and $10,000 in scholarship money[27].

Many other experiments comprised critical research for undergraduate and graduate students. These educational venues are summarized in Thomas et al, 2006[13]. Looking forward, using the ISS as an educational platform will be taken to a new level as the ISS National Laboratory develops. The America Competes Act (2007) provides direction to NASA to include STEM educational activities as a high priority. Educational activities are a key component of the National Lab legislation, and planning is underway with commercial, academic and other US agency partners to develop novel programs and experiments targeting student involvement[28].

IV. Supporting Future Exploration: Science After the First Ten Years

Publications of ISS scientific results, one metric used to measure success of the research program, have shown steady increases in all scientific research areas on the ISS (Fig. 5). To date, we have identified roughly 200 publications directly resulting from research on the ISS.

Building from these successes, engineers and scientists from around the world are working together to refine their relationships and build from their experiences conducting early science to ensure maximum utilization of the expanded capabilities aboard ISS. These capabilities have already enabled scientists to replan their experiments in real time, and immediately respond to new observations and unexpected results by performing new experiment runs. Other research builds from questions arising from early ISS science results.

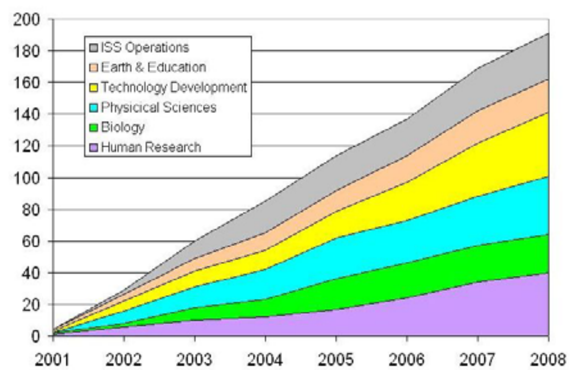

Figure 5. A compilation of number of publications resulting from research aboard the ISS. Each discipline has produced a steady stream of published results, one metric for assessing scientific productivity.

New experiments aboard the ISS include a broad range of science:

- Coordinated human research experiments that collaborate with international partners' science objectives and facilities, including shared baseline data collection and inflight sampling, with the goal of understanding integrated causes and effects of changes in the human body.
- Research using new science racks (described by [29]), including the Fluids Integrated Rack (FIR), the Combustion Integrated Rack (CIR), and Materials Science Research Rack (MSRR), will enable new experiments exploring combustion, fluid behavior and heat-dependent crystallization patterns in metal alloys.
- Exploration Technology Development will build from early experiments on materials exposure, smoke generation, liquid fuel management, and environmental monitoring.
- The new Window Observation Research Facility (WORF) will provide capabilities to support remote sensing instruments, enabling Earth Science research that will, for example, document crop health and test the utility of blue-green bands for ocean research.

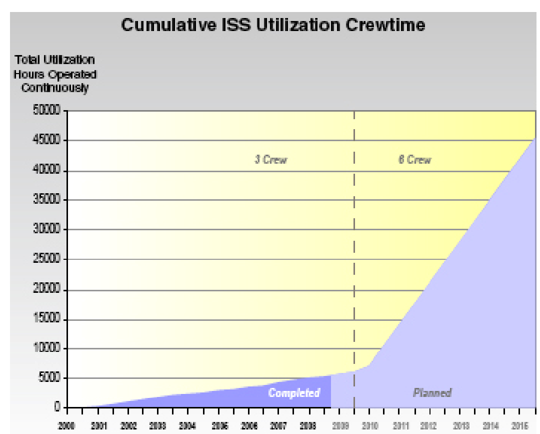

Figure 6. Graph showing the cumulative amount of crew time available for research on ISS.

With a large body of published scientific results from the ISS, new science facilities, mature operational protocols for science operations, the realization of international scientific partnerships and new opportunities for scientific collaboration, and the increased crew size in the near future, the research from ISS is on the rise. During 2008, there were solicitations for new NASA research proposals for potential promotion to flight on ISS in the areas of human research for exploration, fluid physics, and life sciences. Early participation in the ISS National Laboratory was also begun, with Memoranda of Understanding or Space Act Agreements signed by NASA and the National Institutes of Health, U.S. Department of Agriculture, and three commercial entitied. Figure 6 illustrates the projected increase in cumulative crew time for conducting scientific research on ISS. We anticipate that this graph also approximates the increased rate of scientific returns in the future.

As ISS science activities and operations continue, scientific data derived from earlier experiments will be re-examined, mined, and assembled with new data and findings—perhaps data from other fields. We anticipate successful ISS research will be used to seed new ideas and hypotheses to be tested on future missions.

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